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K_{Iscc} Stress-Corrosion Tests of HY-140 Welds for DSRV-2

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ABSTRACT

K_{ISCC} stress corrosion fracture toughness measurements were made on the welds of 2" thick HY-140 material intended for use in the DSRV-2. The welds were of the standard TIG type and were made by Excelco Products, Inc. using the same joining practice as that for the pressure spheres. A K_{ISCC} value of 195 Ksi $\sqrt{in.}$ indicated a high level of resistance to stress corrosion cracking, very nearly equal to the toughness of HY-140 base metal in an air environment ($\approx$ 200 Ksi $\sqrt{in.}$). At this level of fracture toughness critical flaw sizes are of sufficient size that they should be easily detected during non-destructive inspection.

PROBLEM STATUS

This is an interim report on one phase of the problem; work is continuing.

AUTHORIZATION

This research was supported by the Deep Submergence Systems Project of the Department of Defense, NRL Problem F01-17, P07-0001. Mr. Harold Bernstein is the Project Engineer.

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BACKGROUND

K_{ISCC} fracture toughness measurements have been made on the welds of HY-140 material welded by Excelco Products, Inc. using the same joining practice as that for the pressure spheres of the Navy deep submergence rescue vessel number 2. K_{Ic} measurements were also made on the same welds for reference purposes. The weld was the standard tungsten-arc inert-gas shielded TIG type. HY-140 steel is a quenched and tempered 5 Ni-Cr-Mo-V composition. The average tensile yield strength, as quoted by the producer, was above 140,000 psi for both base plate and weld.

The objective of this investigation was to determine if the weld had a good resistance to stress corrosion cracking (SCC) in a salt water environment. The resistance was measured by the value obtained for a fracture-toughness stress intensity parameter, K_{ISCC}. SCC can be expected to occur at a fracture stress intensity above this value in the specific environment.

TEST PROCEDURE

The procedure used to determine K_{ISCC} is essentially the same as that reported on by B. F. Brown (1). Four notched bend bars numbered HYD-1 through HYD-4 were used for the stress-corrosion tests. The dimensions of the bars are shown in Figure 1 with the specimen width, B, and specimen depth, D, each equal to 1.8 inches. Fracture toughness measurements were made only on the middle of the weld since sufficient material was not available to evaluate each area of the weld. A previous study on 18% Ni maraging steel indicated the center of the weld to be the least tough, though this may vary with material (2). Three bars were tested in the synthetic

sea water environment while the fourth, HYD-4, was tested in air.

For salt-water tests, a 3-1/2 percent solution of NaCl in distilled water was placed in a plastic container surrounding the notch area (Figures 2 and 3). The bar was stressed by three-point bending to determine the highest steady load which could be applied before slow crack growth took place continuously.

The desired period under steady load was twenty hours since significant effects of SCC normally appear within this time. The period was divided into three working days with a no-load interruption (while maintaining the corrosive environment) during off hours. The records of a complete test are shown in Figures 4 and 5. The dried bar finally was broken in air with a rising load (Figure 6) and the crack lengths were measured at the different stages of testing (Figure 7). The resistance to stress-corrosion cracking, K_{ISCC}, was calculated from the data shown in Table 1. More details on test procedure are given in Appendix A.

Because of difficulties in operating the testing machine, which are discussed in Appendix A, only one test (HYD-[illegible]) lasted close to twenty hours. The partially finished tests, including the one in an air environment, are reviewed in Appendix A.

K_{ISCC} CALCULATIONS

The evaluation of K_{ISCC} was based on the results plotted in Figure 8. These data included the parts of tests which were unaffected by the difficulties encountered in testing machine operation. A conservative value for K_{ISCC} of the TIG weld was judged to be 19[illegible],000 psi$\sqrt{in}$. for an exposure up to

twenty hours in a quiet pool of synthetic sea water. This is practically the same toughness that HY-140 base metal has shown in an air environment (estimated to be about 200,000 psi $\sqrt{in}$).

Calculations for critical flaw size (equation in Appendix A) indicated that the HY-140 weld would tolerate long surface cracks up to 0.4 inch deep at a nominal stress equal to yield stress (σ_{YS}). Shorter surface cracks of semi-elliptical shape could reach a size of about 3/4 inch deep and 3 inches long before instability occurred at a stress level of 0.9 σ_{YS}. It is reasonable to assume that flaws which might be present in welds of DSRV-2 pressure spheres would be detectable by nondestructive inspection in sizes below the calculated critical values for fracture instability.

CONCLUSIONS

The following conclusions were inferred from the stress-corrosion test.

a. A TIG weld in HY-140 plate two inches thick maintained a high level of fracture toughness (195,000 psi $\sqrt{in.}$) during an exposure of about twenty hours to synthetic sea water. The high value is an indication of good resistance to stress-corrosion cracking in sea water.

b. Crack flaws in the weld of less than critical size for fracture instability are expected to be detectable by non-destructive inspection.

c. The experimental procedure illustrated a method of measuring K_{ISCC} in a salt-water environment by three-point loading of a precracked steel bar. Stable electronic control of the hydraulic loading system was a requirement.

REFERENCES

(1) Brown, B. F., et al., "Marine Corrosion Studies; Third Interim Report of Progress", NRL Memo Report 1634 (July 1965).

(2) Kies, J. A., Smith, H. L., Romine, H. E., and Bernstein, H., "Fracture Testing of Weldments", ASTM Publication No. 381 on Fracture Toughness Testing and Its Applications. Symposium in Chicago, Illinois, June 21-26, 1964. pps 328-353.

(3) Brown, W. F. Jr., and Srawley, J. E. "Plane Strain Crack Toughness Testing of High Strength Metallic Materials", ASTM Special Technical Publication No. 410.

(4) Tiffany, C. F. and Masters, J. N., "Applied Fracture Mechanics", ASTM Publication No. 381 on Fracture Toughness Testing and Its Applications. Symposium in Chicago, Illinois, June 21-26, 1964. pps 249-277.

APPENDIX A

TEST DETAILS

1. Testing Machine Difficulties. An operational problem in load control - not connected with the basic principle of the corrosion test - reduced the duration of most tests below twenty hours. The difficulty arose from temporary electrical breakdown of some unidentified component of the vacuum-tube servo amplifier which maintained load control. The result was an occasional surge in load which was sufficient in some cases to rupture the bar under test. The malfunction finally was overcome by installation of a new servo amplifier.

A minor problem of load control was encountered in the electrical balancing of the servo amplifier. The load drifted slowly up or down scale from the original setting depending upon the balance control adjustment. Occasional corrections were required since a perfect balance was not obtained.

2. Comments on Incomplete Tests.

a. Bar HYD-1. The loads and related crack depths gave a calculated K_{ISCC} value of 205,000 psi$\sqrt{in.}$ for two 1-1/2 hour periods of constant stress in salt water (Table 2). The load surges which invalidated the remainder of the test are indicated in Figure 9.

b. HYD-2 (Figure 10 and Table 2). This test extended to twelve hours of stress-corrosion exposure before termination by a load surge. The K_{ISCC} value of 21[illegible],000 psi$\sqrt{in.}$ was relatively large but may have been a normal variation in tests of a multilayered TIG weld.

c. HYD-4. This test was run entirely in a room-air environment. The maximum load at which there was no slow crack growth did not seem to be as

sharply defined as the corresponding point in the salt-water tests. The initial value of 19[illegible],000 psi $\sqrt{in.}$ was an estimate of what might be termed the "K_{ISCC} in air" of the weld metal. After an hour, an upward surge of load produced a sudden crack extension (Figure 11). The effect of the surge was to raise K_I values in subsequent stages of the test (Table 3). The higher fracture toughness could be attributed to formation of a work-hardened zone around the crack tip. Sharpness of the crack tip also may have been reduced by plastic blunting. An attempt to restore the original crack-tip condition by additional fatiguing was unsuccessful.

3. Details of Test Procedure. In response to a recent questionnaire, information on this test has been submitted to the ASTM Committee E-24 Sub IV task group. The following details not covered in the text are presented for an additional evaluation of test procedure.

Side notches (Figure 1) were used to restrict plastic flow at the ends of the face notch for better simulation of a plane strain condition. "Plane strain" implied that the crack front was isolated from free-surface effects.

The 20 percent face notch (Figure 1) was extended to a 25 percent depth by addition of a fatigue precrack. Fatigue stressing was accomplished by three-point bending in a tension-tension mode at a nominal fiber stress of one-fourth to one-third of the yield strength. With water in the notch, about [illegible],000 cycles at 80 cycles per minute were required to produce the precrack. After cycling, the bar was heated to remove water.

In the bend test, a transducer was used to measure displacement of the central loading point on the bar with an accuracy of 0.001 inch (Figure 2).

The bending load was applied in small increments and held constant for a short time at each step. If the displacement reading became constant after several minutes at the new load value, it was assumed that continuous slow crack growth had not been produced and a new increment of load was added. As a condition of slow growth was approached, the load increments were reduced to a small value (about one-half of one percent of the total load). A continuous crack growth was assumed to take place when the displacement increased at a rate of about 0.001 inch for each two minutes over a period of ten minutes. The load then was lowered the smallest amount which would stop the upward drift of transducer output. Usually this could be accomplished by a reduction of about one percent in the load setting. The reduced value was the "constant" load used for calculating K_{ISCC}. Occasionally minor reductions in this load had to be applied during a test day to stop any further tendency toward continuous crack growth. Cumulative load displacement measured by the dial gauge also was recorded (Figure 5).

After bar HYD-3 finally was unloaded, the crack area was washed with acetone and dried. This was followed by heat tinting. Fracture of the bar was completed by a standard three-point bend test in air with rising load (Figure 6). Crack depths for each daily test in salt water were distinguishable by the color intensity of the rust layers. The average crack depths were estimated to the nearest 0.005 inch under a microscope (Figure 7 roughly indicated the crack layers).

Marking the crack depth corresponding to a constant load was more of a problem in the air environment (HYD-[illegible]) except for the heat tint on the last day.

A fatiguing operation was tried to mark the stages in crack growth (Figure 11) but this method was only moderately successful because the secondary fatigue cracks grown from a natural crack were not as sharply defined as the fatigue precrack started from the machined face notch.

[illegible]. Formulas

a. In ASTM publication STP 410,([illegible]) W. F. Brown, Jr. and J. E. Srawley gave an alternate formula for calculating K_I from the bend specimen. Their polynomial formula, corrected for side notches as shown below, resulted in K_I values about three percent lower than the values from the Kies formula in Table 1.

$$K_I = \left(\frac{B}{B_N}\right)^{1/2} \frac{3\, PL_1\, a^{1/2}}{BD^2} \left[1.96 - 2.75(a/D) + 13.66(a/D)^2 - 23.98(a/D)^3 + 25.22(a/D)^4\right]$$

b. Irwin equation for critical flaw size:

$$a_{cr} = \frac{QK_{IC}^2}{1.21\pi\sigma^2} \quad \text{(for SCC, the value } K_{ISCC} \text{ would be used in place of } K_{IC}\text{)}$$

Long surface flaws (worst case), $\sigma = \sigma_{YS}$, $Q = 0.8$[illegible]

Semi-elliptical surface flaws ($a = c/2$), $\sigma = 0.9\,\sigma_{YS}$, $Q = 1.$[illegible]

Q values are from p. [illegible], ASTM publication STP [illegible]1 ([illegible]).

APPENDIX B

DATA ON MATERIALS AND WELDING FROM MANUFACTURER'S REPORTS

1. Chemical Composition (Percent by weight except gas analysis in parts per million).

	2-inch Plate HY-140 Steel (U.S. Steel Corp.) Heat No. L50933 Ladle Analysis	0.0[illegible]2-inch AX-140 Weld Wire (Air Reduction Co.) Heat No. [illegible]
Carbon	0.11	0.094
Manganese	0.73	1.72
Phosphorus	0.004	0.009
Sulfur	0.004	0.008
Silicon	0.29	0.34
Copper	0.06	0.098
Nickel	5.20	2.18
Chromium	0.56	1.05
Molybdenum	0.53	0.61
Vanadium	0.10	0.0098
Titanium	0.01	0.009
Aluminum	----	0.04
Zirconium	----	< 0.0088
Hydrogen	----	0.7 ppm
Oxygen	----	27 ppm
Nitrogen	----	33 ppm

DATA ON MATERIALS AND WELDING FROM MANUFACTURER'S REPORTS (Continued)

2. <u>Welding Procedure</u> (Excelco Developments, Inc.).

Process - standard TIG weld, heliarc, horizontal position, preheat 225 to 300°F, interpass heat 225 to 300°F.

Geometry of weld joint - double J, 40 degree included angle, 1/8 inch groove radius, 0.06 inch land.

Filler metal size - 0.062 inch diameter.

Electrode - 1/8 inch diameter tungsten.

Arc travel speed - 6 in/min, all weld passes.

Nominal count of passes - side No. 1, 68 passes; side No. 2, 80 passes.

Pass conditions - No. 1 side; 1st pass, wire speed 9 in/min. 190 amps, 10 volts; 2nd pass, 15 in/min wire speed, 220 amps, 11 volts.

No. 2 side; 1st pass, no wire, 240 amps, 11-12 volts.

All other passes, wire speed 15 in/min, 240 amps, 11-12 volts.

Weld conditions - gas flow 25 cu ft/hr., purge flow 15 cu ft/hr. fixtures were used and weld was restrained, chill blocks were not employed.

Inspection - X-ray and dye penetrant.

[illegible]. Mechanical Properties

[illegible]-inch plate (U. S. Steel mill tests):

Average tensile properties, yield at 0.2% offset - 142,000 psi, tensile strength - 1[illegible]1,000 psi, elongation in 2 in. - 18.[illegible]%, reduction of area - [illegible]%, test fractures were all fiber.

Other properties, passed drop weight test at -[illegible]0°F, grain size was No. [illegible] ASTM.

Weld (Excelco data), procedure qualification with same wire and similar [illegible]-inch thick HY-1[illegible]0 steel plate, 1[illegible] tensile tests, transverse TIG weld.

	Yield Strength at 0.2% Offset (psi)	Tensile Strength (psi)	Elongation (%)	Reduction of Area (%)	Break
Minimum	1[illegible],000	1[illegible],000	17	[illegible]2	Eight tests broke
Maximum	1[illegible],000	1[illegible],000	21	[illegible]5	outside weld and
Average	1[illegible],000	1[illegible],000	19	[illegible]	seven broke inside

Typical Rockwell hardness values (R_c):

	Base Metal	Weld Metal
Minimum	[illegible]	[illegible]
Maximum	[illegible]	37
Average	[illegible]	[illegible]

TABLE I. K_{ISCC} AND K_{Ic} VALUES OF WELD IN HY-140 PLATE 2 INCHES THICK

Bend-bar stress corrosion tests, three-point loading.
Bend span of 14.4 inches, L_I = 7.2 inches.
Ambient temperature ≈ 78°F.
At the start of each test day, a new salt solution was used for environment.

Test Bar	Environment	D Bar Depth (in)	B Bar Width (in)	BN Width Between Side Notches (in)	P Constant Load Just Below Yielding (in)	a Crack Depth Corresponding to Constant Load (in) (1)	K_{ISCC} Stress Intensity Factor (1000 psi $\sqrt{in}$) (2)	Remarks
HYD-3	3-1/2% NaCl in distilled water.	1.80	1.80	1.60		(0.390)		Depth of fatigue precrack.
					40,800	0.415	194	Value at end of first day.
					40,400	0.425	195	Value at end of second day.
					40,000	0.445	200	Value at end of third day.
					P Maximum Load	a Minimum Crack Depth	K_{Ic} Minimum	
	Air				43,000	0.445	215	Final rising-load test in air after three days in salt water.

NOTES (1) Crack depths were estimated by inspection of the bar after fracture.
(2) K_I values were calculated by Kies's equation corrected for side notches:

$$K_I = (B/B_N)^{1/2}(L_I/D^{3/2})\,R\,(P/B), \text{ where } R = 2.060\,(1/\alpha^3 - \alpha^3)^{1/2} \text{ and } \alpha = (1 - a/D).$$

No adjustment was made for plasticity.

TABLE 2. K_{ISCC} VALUES OF WELD IN HY-140 PLATE 2 INCHES THICK

Bend-bar stress corrosion tests, three-point loading.
Bend span of 14.4 inches, L_1 = 7.2 inches.
Ambient temperature ≈ 78°F.
At the start of each test day, a new salt solution was used for environment.

Test Bar	Environment	D Bar Depth (in)	B Bar Width (in)	B_N Width Between Side Notches (in)	P Constant Load Just Below Yielding (lb)	a (1) Crack Depth Corresponding to Constant Load (in)	(2) K_{ISCC} Stress Intensity Factor (1000 psi $\sqrt{in}$)	Remarks
HYD-1	3-1/2% NaCl in distilled water.	1.80	1.80	1.59	40,600	0.44	203	Value at end of first day.
					40,800	0.45	206	Value or second day just before first m[illegible]ine surge.
HYD-2	3-1/2% NaCl in distilled water.	1.72	1.72	1.54	39,600	0.41	215	Value at end of first day.
					38,200	0.43	215	Value at end of second day.
					37,800	0.45	220	Value on third day just before surge that broke bar.

NOTES: (1) Crack depths were estimated by inspection of the bar after fracture.
(2) K_{ISCC} was calculated by the equation given with Table I.

TABLE 3. K_I VALUES OF WELD IN HY-140 PLATE 2 INCHES THICK

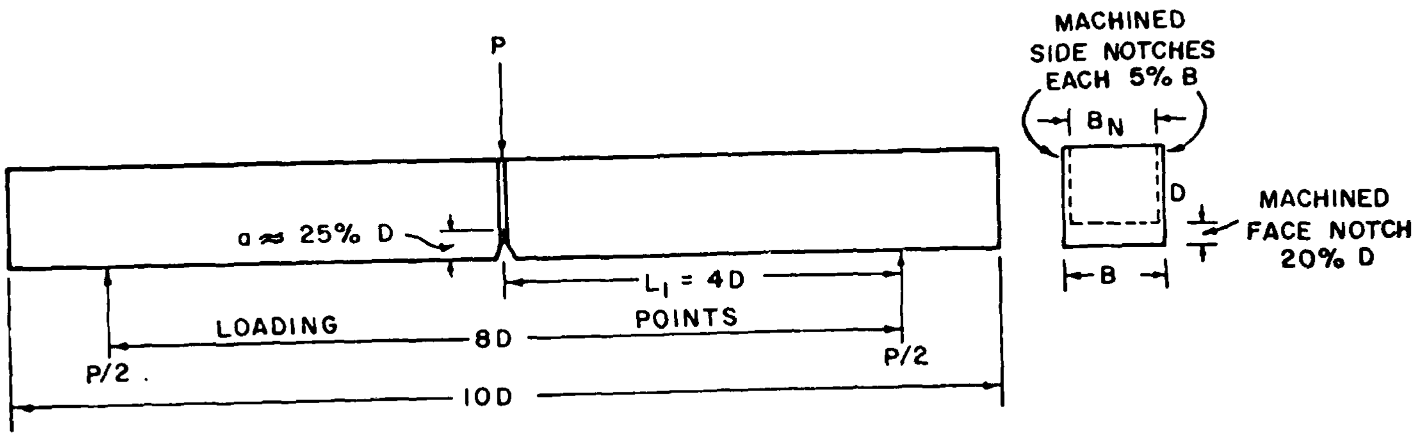
Bend - bar tests, three - point loading.

Bend span of 14.4 inches, L_1 = 7.2 inches.

Air temperature = 75°F, relative humidity ≈ 60%.

Test Bar	Environ-ment	D Bar Depth (in)	B Bar Width (in)	BN Width Between Side Notches (in)	P Load as Described in Remarks Column (lb)	a (1) Crack Depth Associated With Load (in)	(2) K_I Stress Intensity Factor (1000 psi $\sqrt{\text{in}}$)	Remarks
HYD-4	Air	1.80	1.80	1.60	42,200	0.385 min 0.400 max	191 196 Avg. 194	K_I limits for constant load on first day just before machine surge. Average is a probable K_{ISCC} for air environment.
					45,300	0.400	211	K_I for maximum load in machine surge.
					46,000	0.400 min 0.410 max	214 217 Avg. 216	K_I for maximum load on second day after surge and second fatigue crack.
					43,200	0.410 min 0.420 max	204 206 Avg. 205	K_I limits for constant load on third day.
					42,800	0.420 min	204 min	K_I for maximum load to break bar in rising-load test after third fatigue crack.

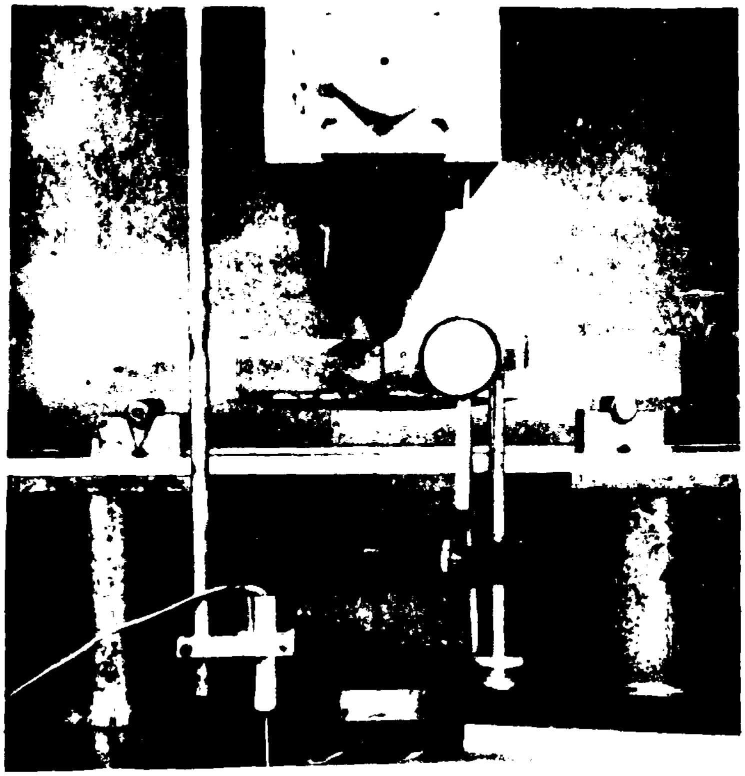
NOTES: (1) Crack depths were estimated by inspection of the bar after fracture.
(2) K_I values were calculated by the equation given with Table 1.



Notches were machined with an included angle of 45° and a root radius ≈ 0.01 inch. The face notch was extended about 5% of D by fatiguing at a fiber stress below $\sigma_{YS}/2$ with water in notch. The bar then was heated at 200°F to expel water.

FIGURE 1

PROPORTIONS FOR SINGLE-EDGE-CRACKED BEND BAR WITH SIDE NOTCHES (THREE POINT LOADED)



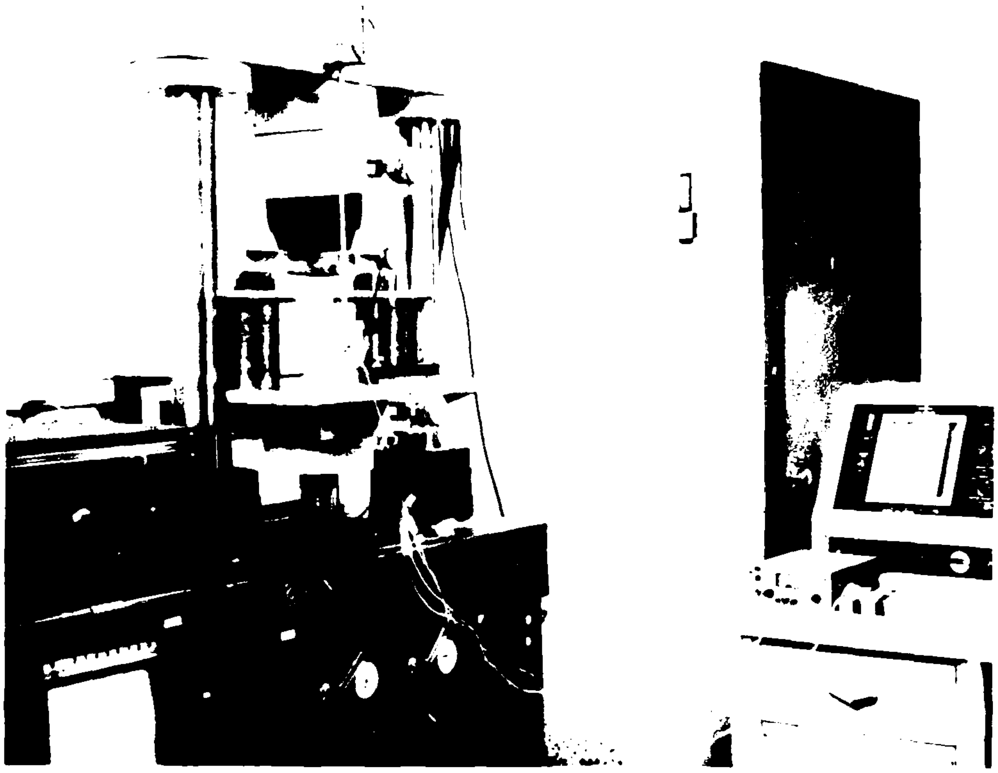
PHD-1122-7-68 FIGURE 2

CLOSE-UP OF THE BEND-BAR STRESS CORROSION TEST

A clear vinyl sheet was wrapped loosely around the sides and bottom of the central part of the bar. The ends of the sheet were fastened with silicone sealant. Synthetic sea water (3-1/2% NaCl in distilled water) was placed in this plastic container so that the crack environment was a quiet pool of salt water exposed to air. Considerable rusting occurred. The liquid was replaced daily with new solution.

The electronic transducer* touching the lower platen was used in recording displacement of the central loading point on the bar. The dial gauge indicated cumulative displacement.

*Sanborn displacement transducer model 7DCDT-250 or equivalent.



PHD-1123-7-68 FIGURE 3

OVERALL VIEW OF INSTRUMENTATION

An X-time strip chart recorder for the displacement transducer is shown on the left. The circuit was adjusted so that one inch of chart width equalled 0.01 inch displacement.

At the far right, the end of the control panel of the UEH testing machine is visible. The machine was set to maintain constant load by closed loop control of the electro-hydraulic system.

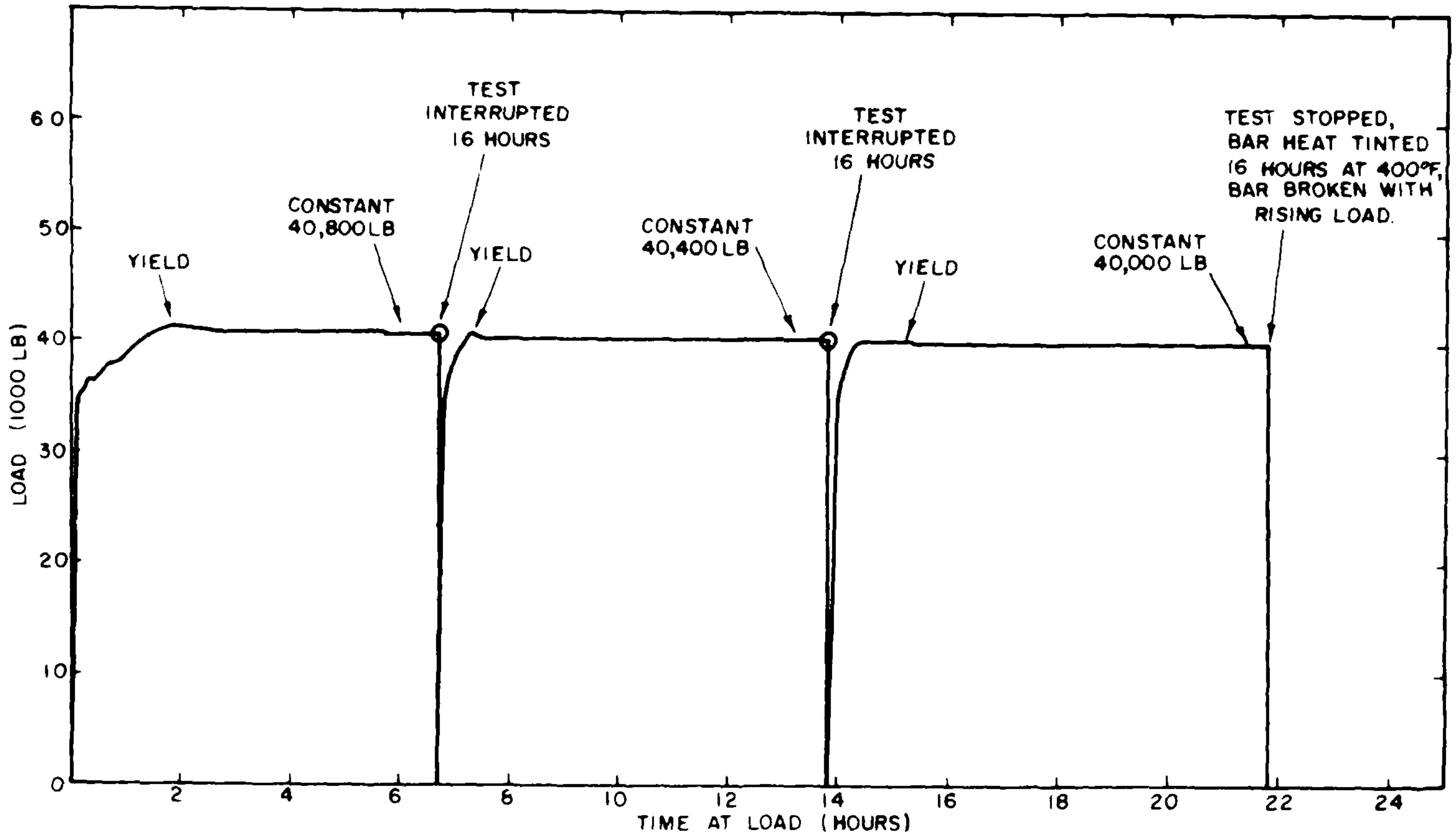


FIGURE 4

EXCELCO WELD IN HY-140 STEEL PLATE 2" THICK

TEST BAR HYD-3, SALT-WATER ENVIRONMENT

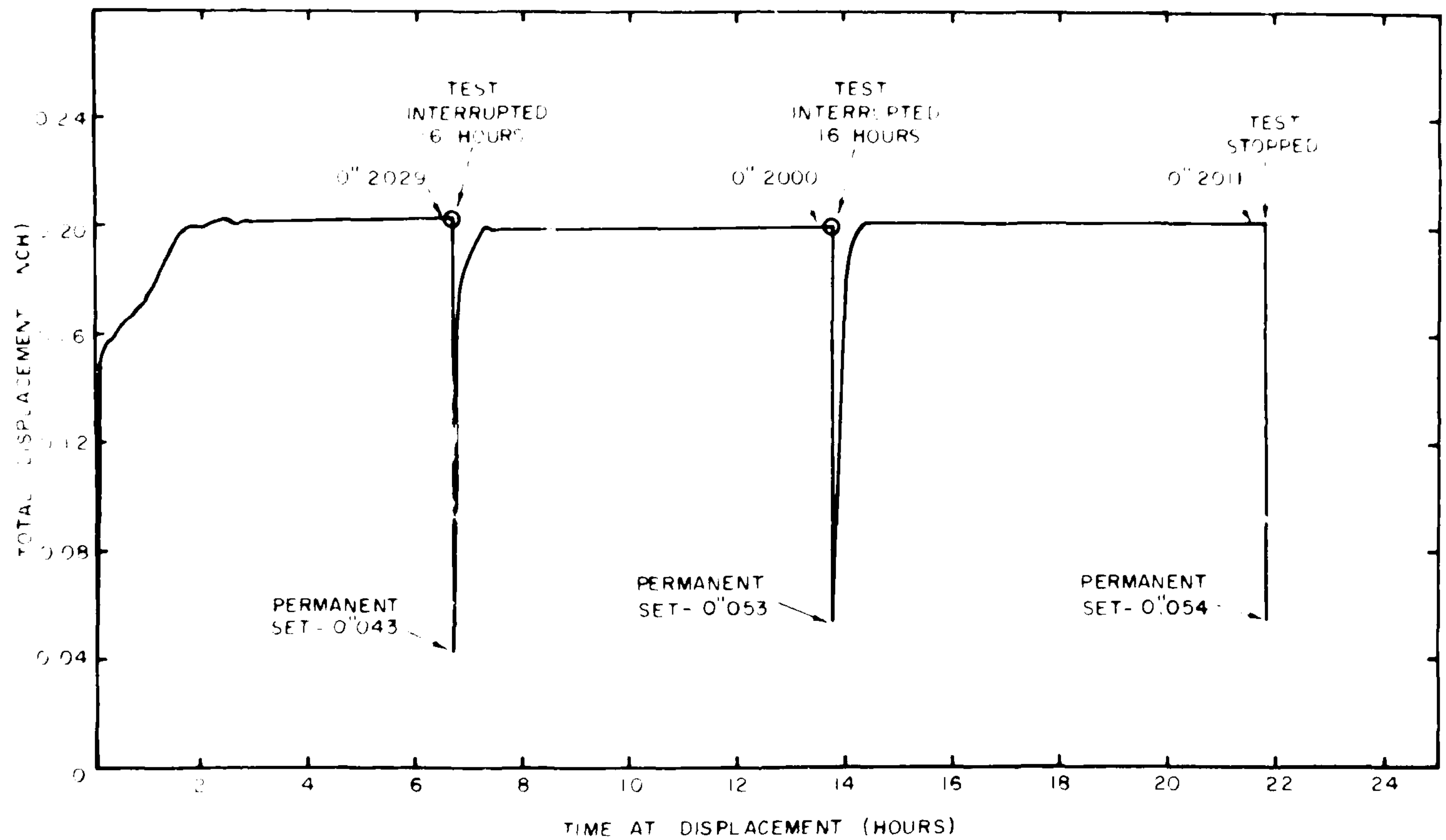


FIGURE 5

EXCELCO WELD IN HY-140 STEEL PLATE 2" THICK
TEST BAR HYD-3, 3-1/2% NaCl IN DISTILLED WATER

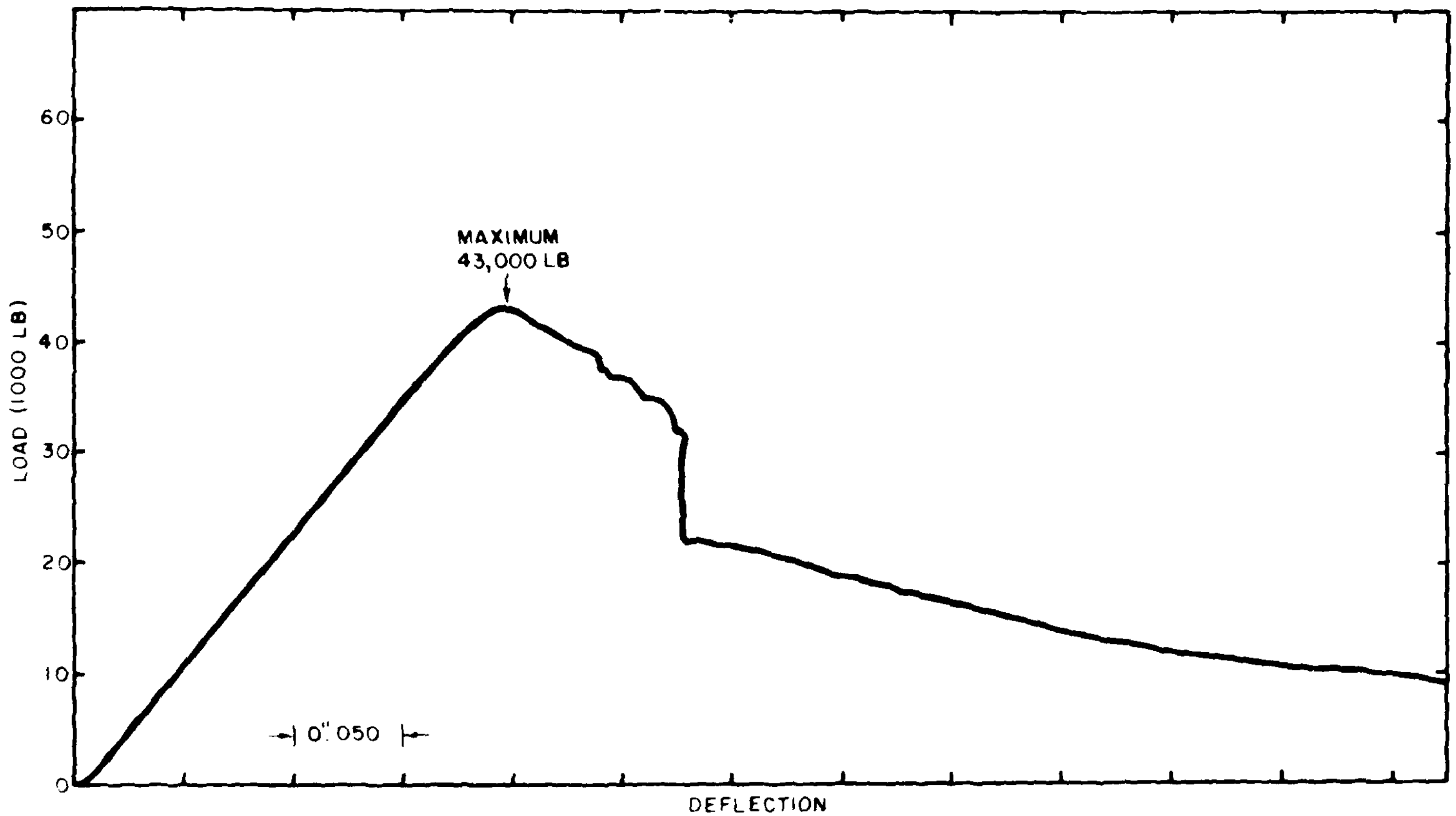
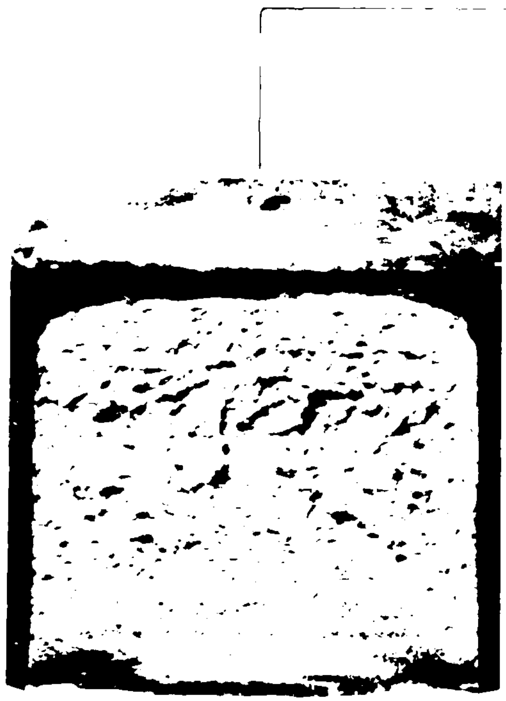
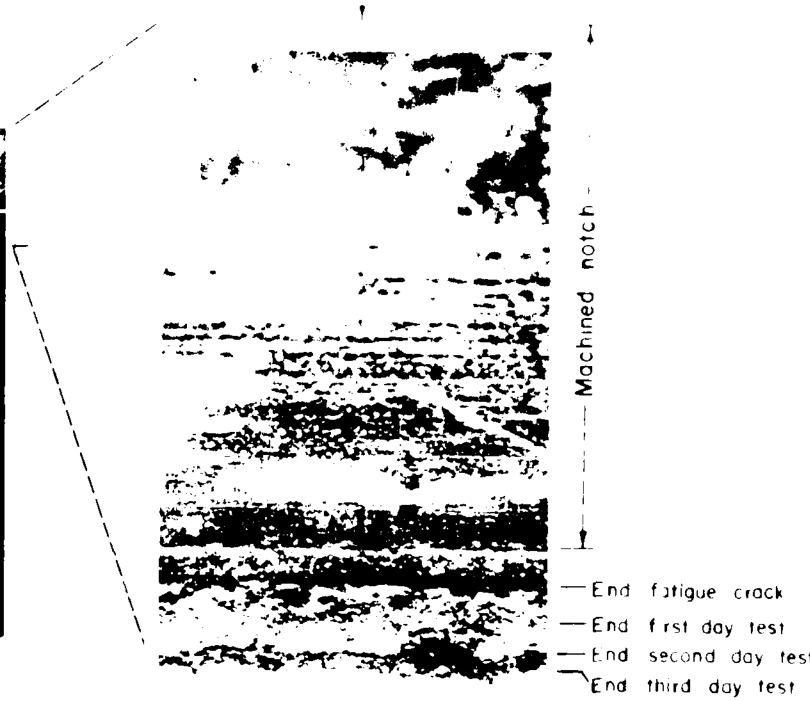


FIGURE 6

EXCELCO WELD IN HY-140 STEEL PLATE 2" THICK
FINAL RISING-LOAD TEST OF BAR HYD-3, AIR ENVIRONMENT AFTER
THREE DAYS IN SALT BATH



Entire fract:re surface of bar
after stress corrosion test.
X2



Enlarged view of crack-depth
area near center of face notch.
X10

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FIGURE 7

DIFFERENTIATION OF CRACK LAYERS IN BAR HYD-3

Variation in intensity of rust color helped in distinguishing the layers.

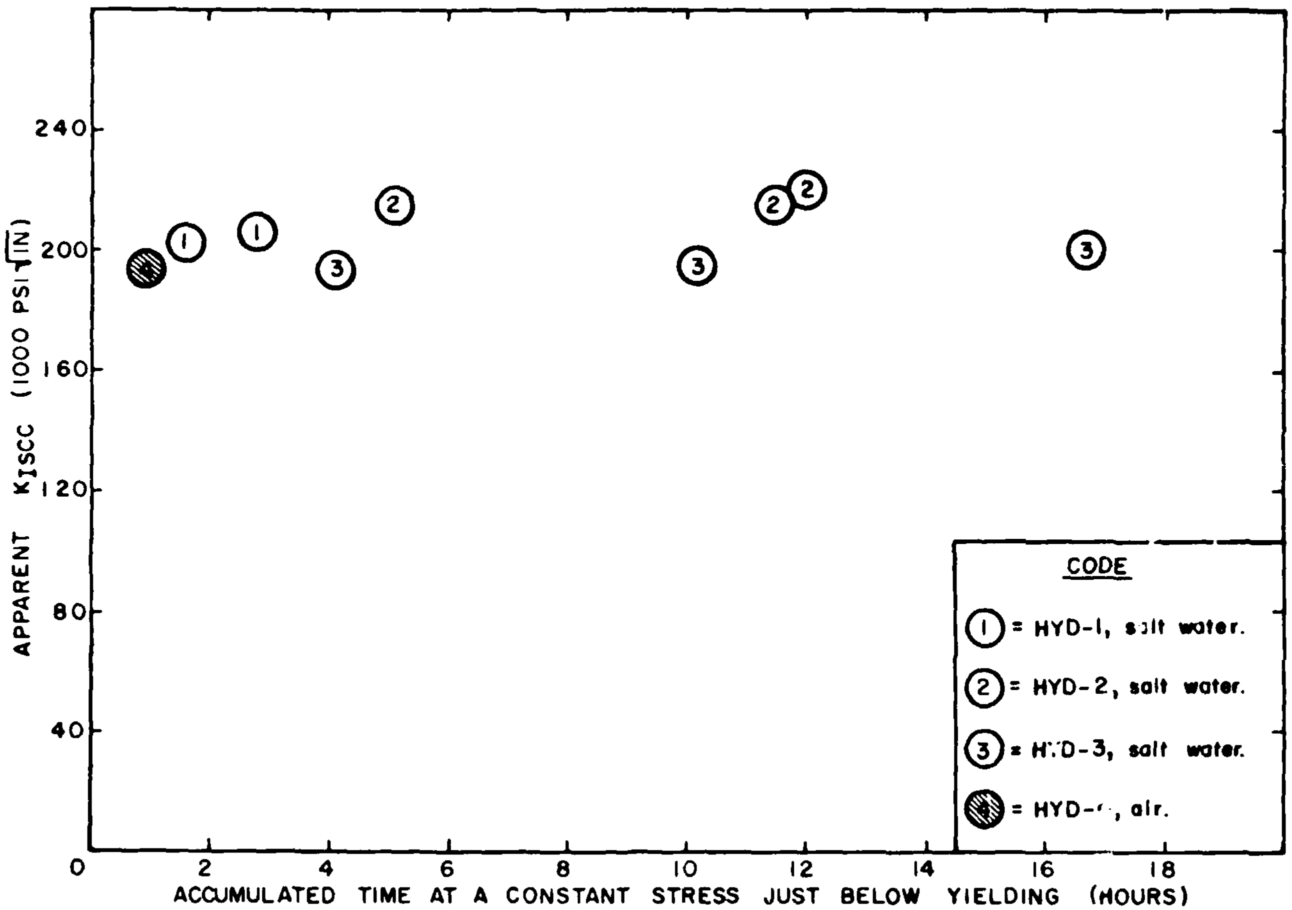

FIGURE 8

K_{ISCC} VALUES INDICATED BY BEND-BAR TESTS ON AN EXCELCO WELD IN HY-140 STEEL PLATE 2" THICK

Only values obtained before machine surges were plotted.

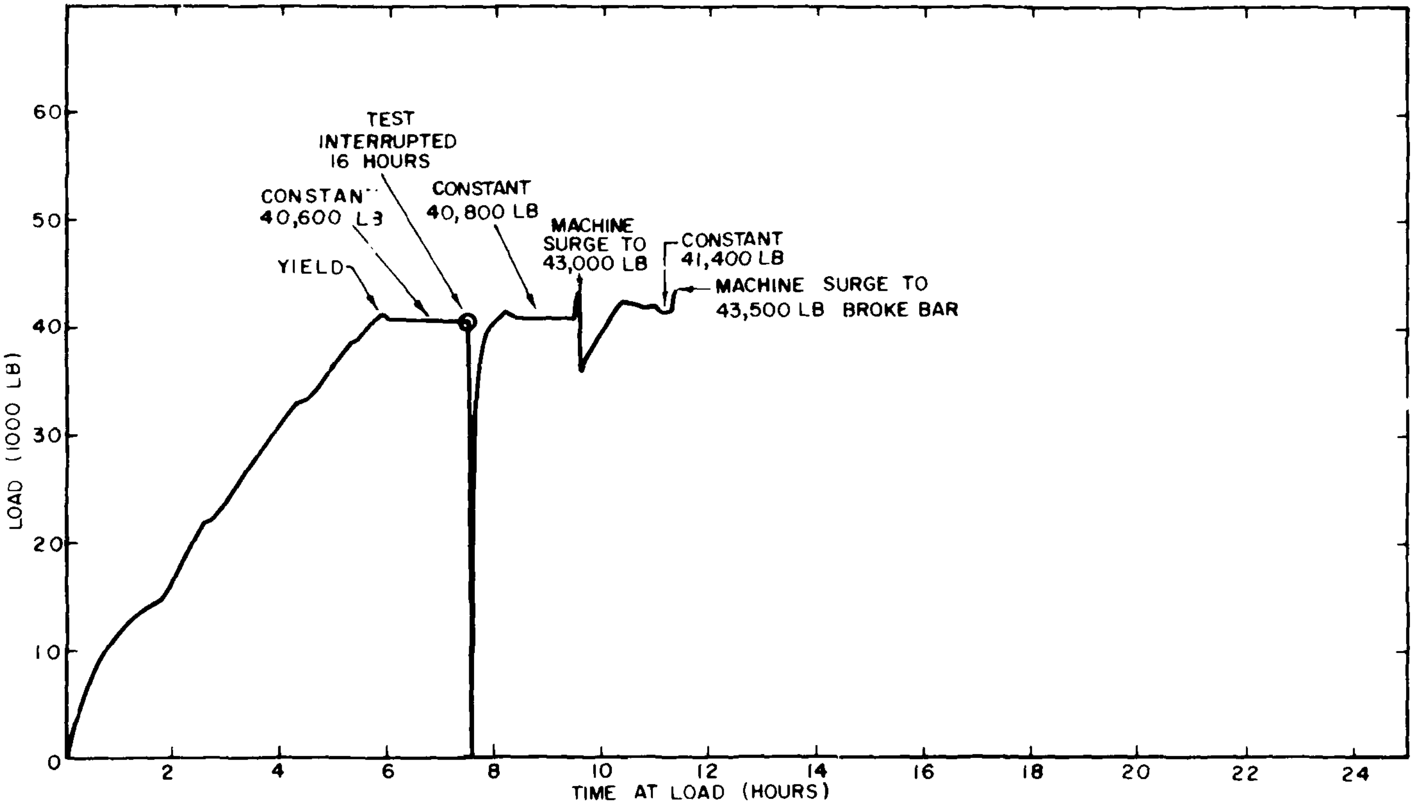

FIGURE 9

EXCELCO WELD IN HY-140 STEEL PLATE 2" THICK

TEST BAR HYD-1, SALT-WATER ENVIRONMENT

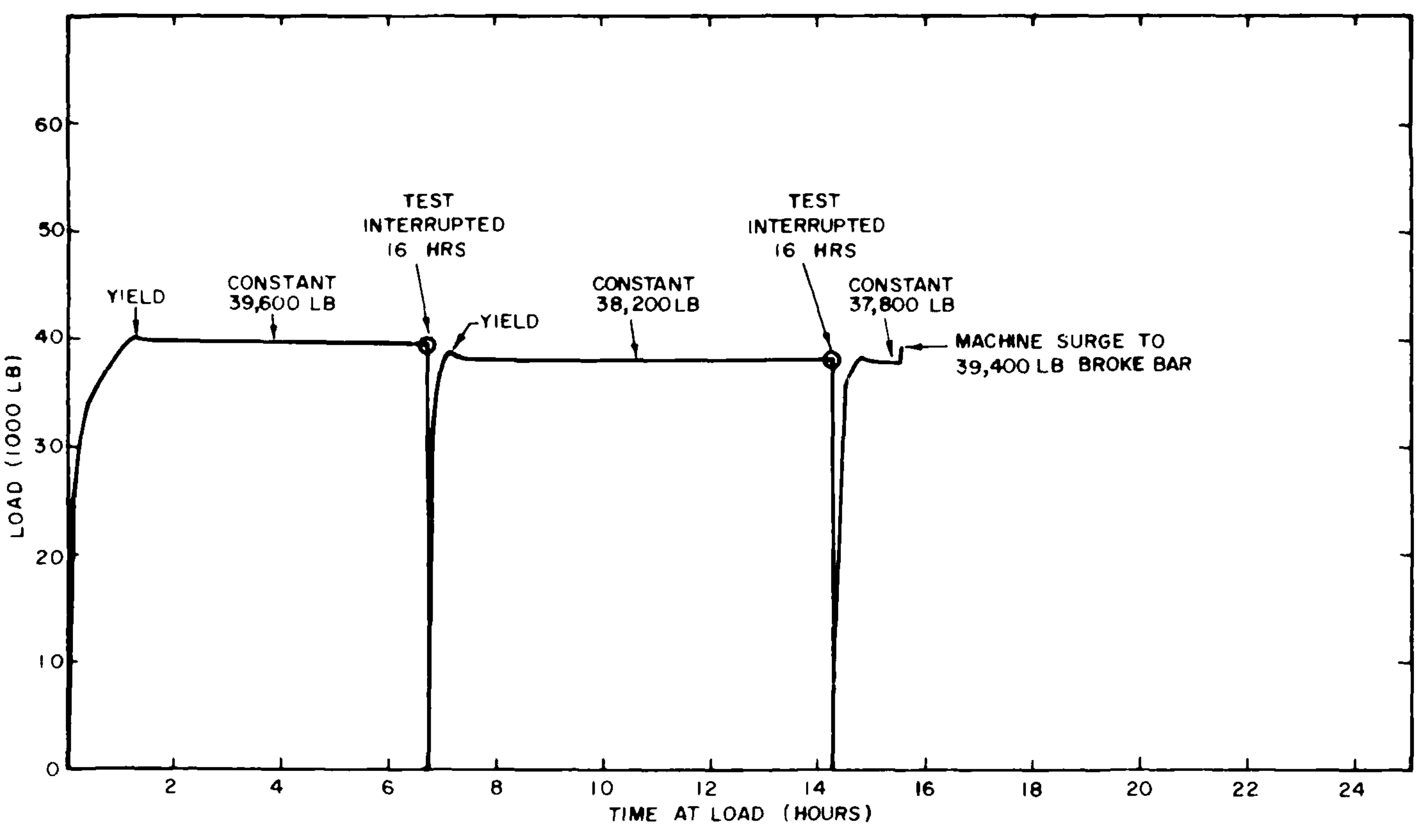

FIGURE 10

EXCELCO WELD IN HY-140 STEEL PLATE 2" THICK

TEST BAR HYD-2, SALT-WATER ENVIRONMENT

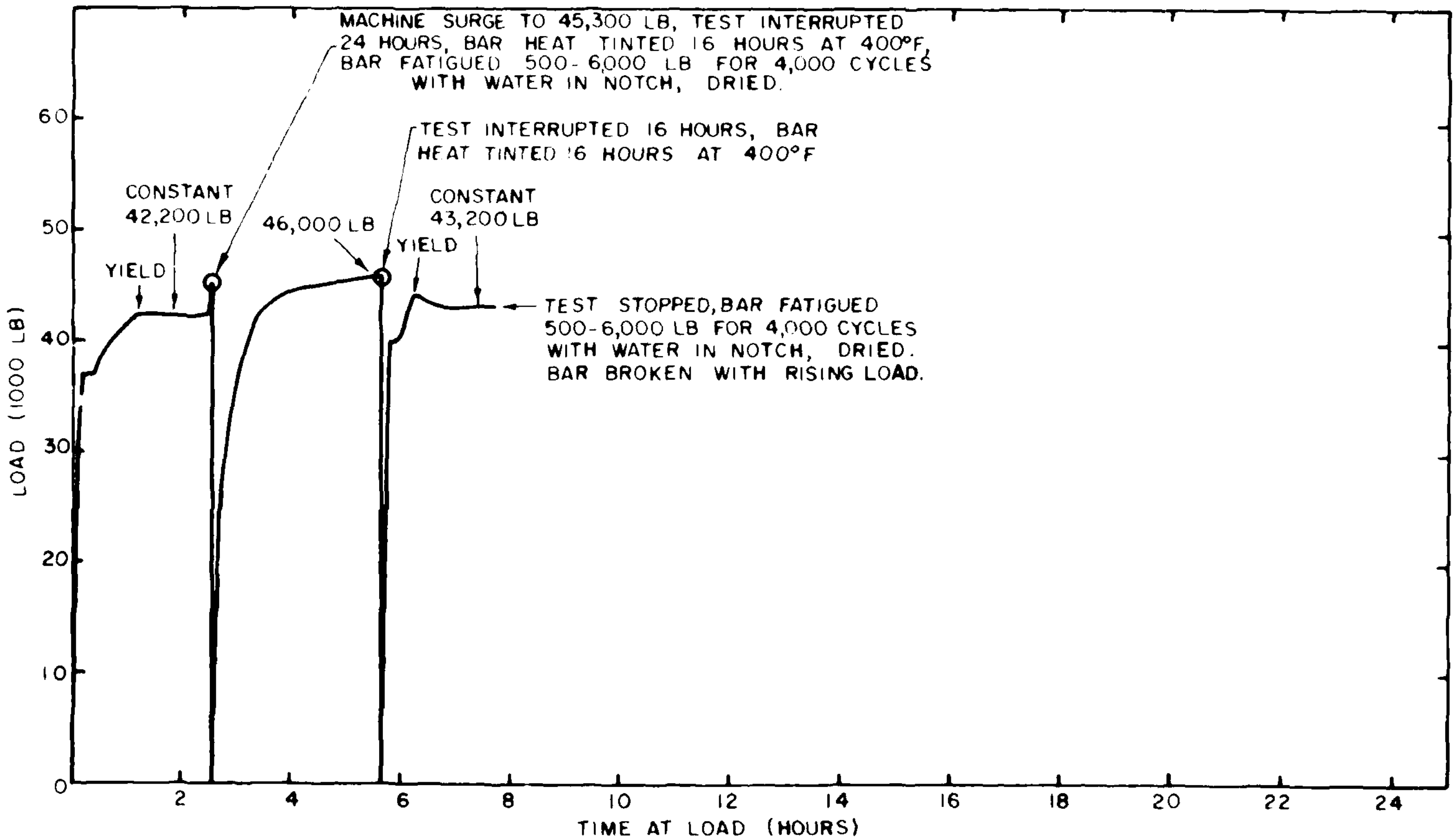

FIGURE 11

EXCELCO WELD IN HY-140 STEEL PLATE 2" THICK
TEST BAR HYD-4, AIR ENVIRONMENT

Temperature: ≈ 77°F, relative humidity: ≈ 60%

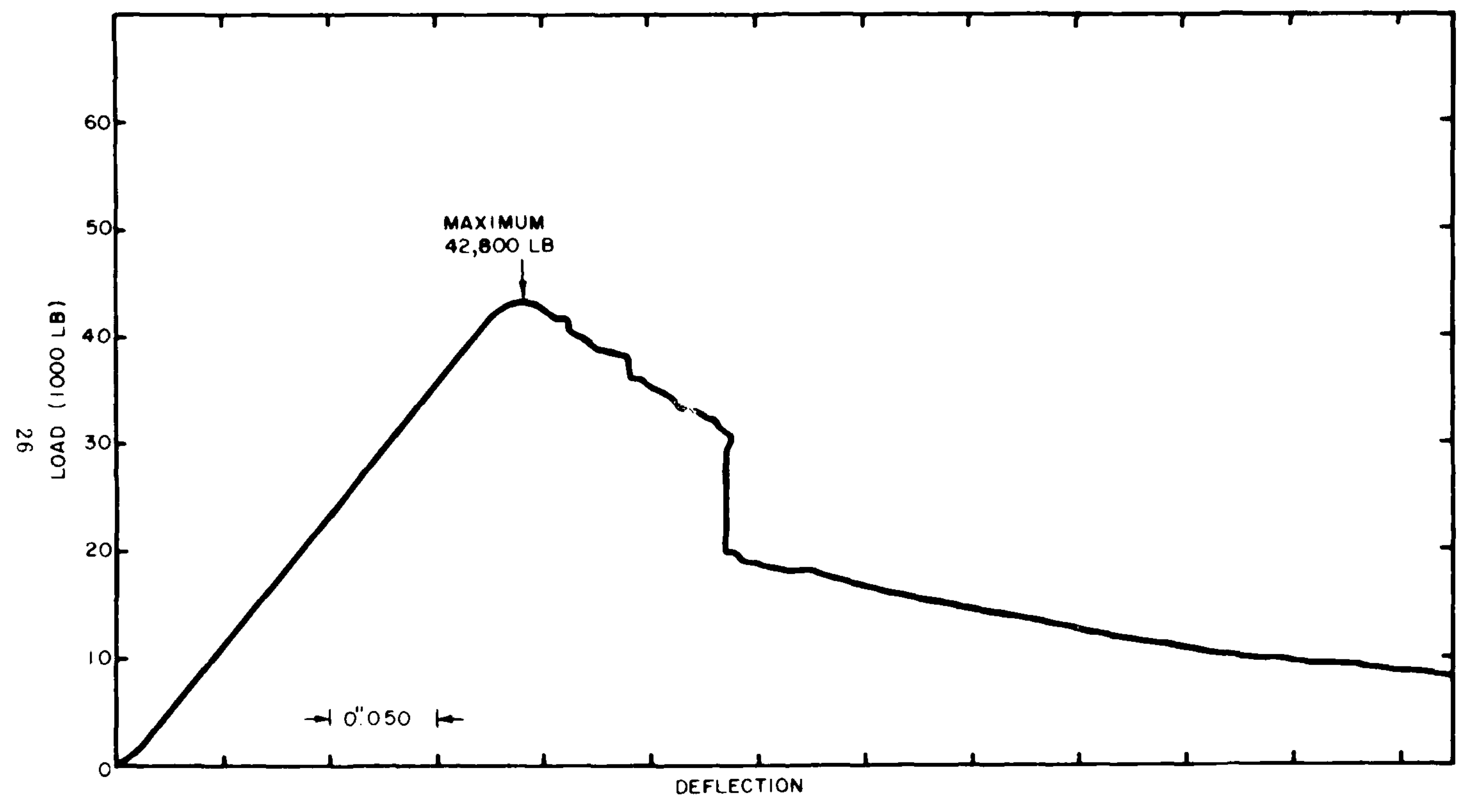

FIGURE 12

EXCELCC WELD IN HY-140 STEEL PLATE 2" THICK
FINAL RISING-LOAD TEST OF BAR HYD-4, AIR ENVIRONMENT

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

K_{ISCC} stress corrosion fracture toughness measurements were made on the welds of 2 in. thick HY-140 material intended for use in the DSRV-2. The welds were of the standard TIG type and were made by Excelco Products, Inc. using the same joining practice as that for the pressure spheres. A K_{ISCC} value of 195 Ksi $\sqrt{in.}$ indicated a high level of resistance to stress corrosion cracking, very nearly equal to the toughness of HY-140 base metal in an air environment ($\approx$ 200 Ksi $\sqrt{in.}$). At this level of fracture toughness critical flaw sizes are of sufficient size that they should be easily detected during non-destructive inspection.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Deep submergence rescue vehicles						
DSRV-2						
Materials						
Steels						
HY-140						
Welds						
Flaws						
Failure						
Stress corrosion cracking						
Testing						